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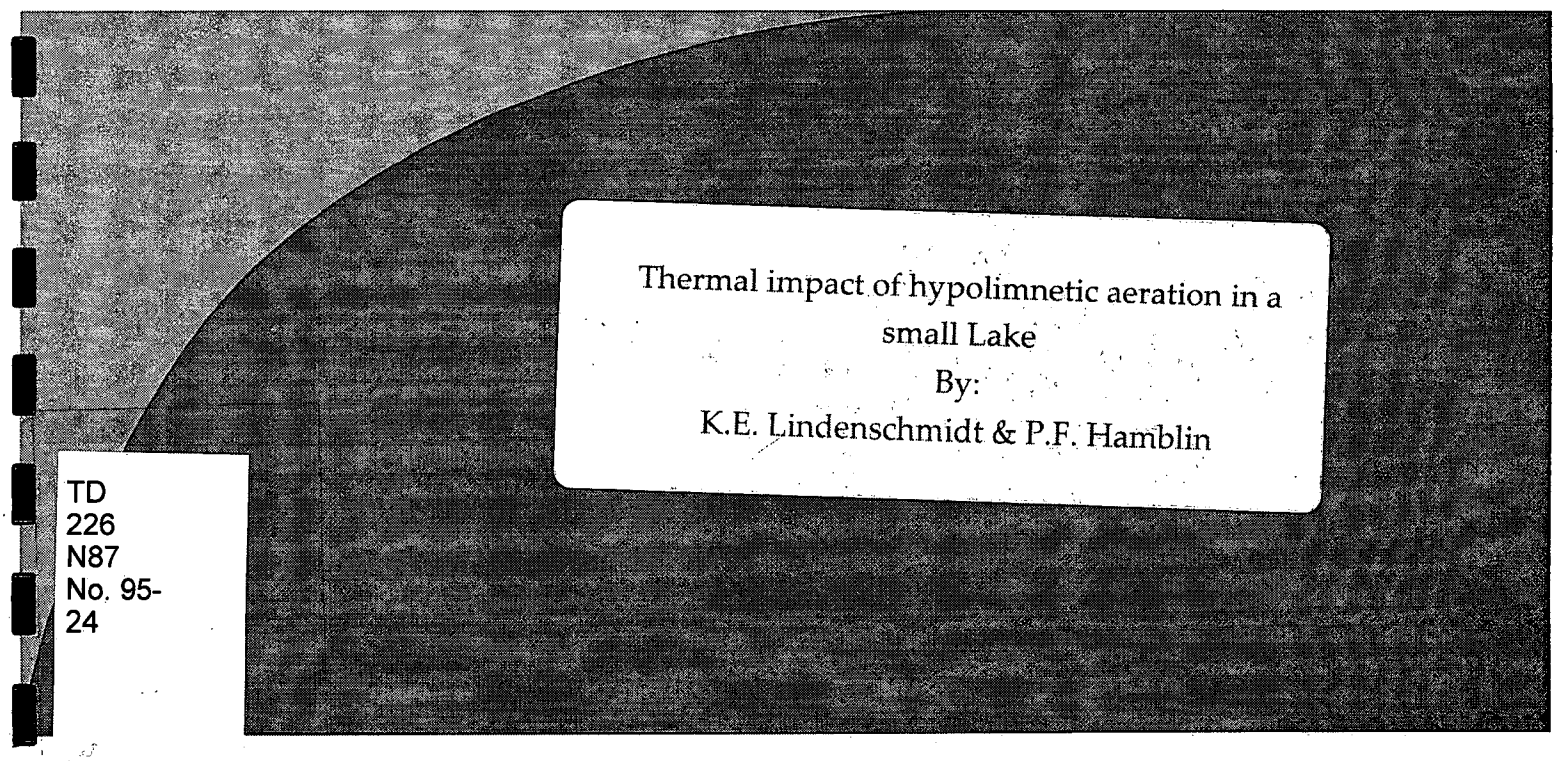

Thermal impact of hypolimnetic aeration in a small Lake

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K.-E. Lindenschmidt
FB Siedlungswasserwirtschaft
Technische Universität Berlin
Strasse des 17 Juni 135 (Sekr. KF 7)
10623 Berlin, Germany

and

P.F. Hamblin[1]
Aquatic Ecosystems Restoration Branch
National Water Research Institute
Burlington, Ontario L7R 4A6, Canada.

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[1]To whom all correspondence should be sent

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MANAGEMENT PERSPECTIVE

Of central interest to the Lake Remediation Project is the restoration of lakes by artificial means. Aeration of lakes and reservoirs via bubble plumes has been a widely used technique in lakes and reservoirs for the past 40 years. A shortcoming of bubbler aeration in water bodies sufficiently deep that they normally stratify in summer is that they break down the stratification of the water column that would reduce the vertical mixing between the surface and bottom layers thereby enhancing the productivity of the lake by the recycling of nutrients. In order to reduce or eliminate this problem a variation of this method has been developed where only the bottom layer or hypolimnion is aerated or stirred. Only recently has bubble plume aeration been incorporated into mathematical models of water quality in lakes and reservoirs but as far as we know no previous attempt has been made to account for hypolimnetic aeration. The goal of this study which has been funded,in part, by the Canada-German Scientific Agreement, is to develop a mathematical model for this type of aeration, included in a water quality model and to test it using an extensive data set collected in a small urban lake, Lake Tegel, located in the city of Berlin, Germany. The principal conclusion of our study is that the network of 15 hypolimnetic aerators employed in Lake Tegel behaved more closely to a conventional bubble plume aerator and that a we have developed a pratical tool for testing various aeration strategies such as the optimal number and duration of a network of aerators in lakes and reservoirs. The new information obtained in this study could be applied to the remediation of such water bodies as Hamilton Harbour where it is desirable to maintain stratification during summer conditions.

Abstract

Hypolimnetic aeration has been a part of a successful restoration strategy for the shallow urban lake, Lake Tegel, in Berlin since 1980. From this time to the present, extensive limnological data on the lake's water quality have been collected which have been used to validate a one-dimensional water quality model. Three cases are discussed, full operation of a network of 15 aerators, intermittent operation as water quality improved and no aeration as is the present situation. The effect of the hypolimnetic aerator is incorporated in a simple fashion in the model as an additional inflow near the bottom, an outflow two metres higher and as a source of mixing energy in the hypolimnion. It was found that aeration has a significant effect on the thermal structure for both full and intermittent operation but that the hypolimnetic aerator model resulted in insufficient mixing of the thermal structure and too uniform a hypolimnion. Improved agreement between model and observations comparable to the unaerated case was obtained for a bubbler plume model. We conclude that the hypolimnetic aerators employed in Lake Tegel functions more like a bubble plume and thus there is considerable mixing between the hypolimnion and epilimnion.

1. Introduction

Hypolimnetic aeration is a widely accepted method for maintaining or restoring oxygenated water in lakes (Ashley, 1988; McQueen and Lean, 1986). Although it is designed to minimise the mixing between the hypolimnion and the epilimnion, by the nature of its operation it is nearly impossible to avoid some mixing between these layers which has the unwanted consequence of reducing or eliminating the stratification Klapper (1991). To date, limited effort has been made in estimating the effects of one or more hypolimnetic aerators on the thermal regime of lakes. Our approach is to determine their impacts by means of mathematical modelling of the lake water quality with special attention to the thermal regime and with reference to an extensive collection of field observations of both the natural and disturbed states. The only mathematical model that we are aware of that simulates the impact of artificial stirring on the water quality is DYRESM which has been extended to treat point

source bubbler plumes (Patterson and Imberger, 1989; Schladow and Fisher, 1995). The goal of this paper is to incorporate a model of the stirring effects of a network of hypolimnetic aerators in the DYRESM water quality model and to present results on its impact on the annual thermal regime of a small urban lake.

2. Model Description

We make the assumption which is similar to other applications of water quality models to lakes (Patterson et al.,1984), CEQUAL (USACE, 1986) and MINLAKE (Riley and Stephan, 1988), that it is justifiable to treat the evolution of the seasonal structure of water properties as a horizontally averaged, time dependent problem involving only their vertical variation. While progress is being made in the development of higher dimensional models we are interested in simulating at least a four year period which would be computationally too expensive despite the likely superior accuracy. The model DYRESM (Patterson et al., 1984) was chosen as the basic model on account of its firm theoretical foundation, its widespread applicability to a range of lake sizes and types in previous studies and because it has already been applied to aeration problems in two reservoirs (Patterson and Imberger, 1989; Schladow and Fisher, 1995).

The fundamental time step in the model is daily although subdaily steps are permitted. Once a day latent and sensible heat transfers are computed from measured surface air temperatures, wind speeds and relative humidity. In this study both incoming global solar radiation and long-wave radiation are observed daily. Outgoing long-wave radiation as computed from the modelled water surface temperature completes the heat budget. Another driving factor for the thermal regime is basin hydrology. In keeping with the one-dimensional concept of the model structure the three-dimensional processes of tributary inflow and lake outflow are represented in parametric form. For a detailed presentation of the physics the reader is referred to Fischer et al. (1979) and Imberger and Patterson (1981) but briefly the inflow is inserted at a level where its density matches the lake density after making allowances for mixing of the inflow with the surrounding less dense lake water. Similarly, the process of selective withdrawal

whereby water other than surface water is drawn into the outflow depending on the strength of the outflow and the stratification of near surface waters is taken into account. Once the heat input to the water body is determined it is redistributed from the surface by vertical mixing and in the case of shortwave radiation by absorption through the water column. The absorption or extinction coefficient is an input parameter in the model and is taken from Secchi disc readings from time to time and the usual empirically based relation between Secchi and light extinction. Near the surface heat is mixed according to an integral thermocline model which takes account of stirring due to wind and wave breaking, current shear due to basin scale internal waves and convective cooling at the surface. In this application to Tegel Lake it is assumed that internal seiches may be excited by the component of wind forcing along the major lake axis every three hours. Below the thermocline vertical mixing of heat is based on a semi-empirical approach whereby a fraction of the dissipation of turbulent kinetic energy goes to increase the potential energy of the water column. As well as artificial stirring mixing in the hypolimnion depends on stirring by winds and river inflows and the overall rate of stratification. The fraction of energy dissipation is not regarded as a free parameter but has been fixed by previous applications (Boyce et al., 1993).

The water density is a function of temperature, total dissolved solids and suspended solids. For this reason, we have retained salinity and turbidity but in such a shallow lake do not expect them to play a substantial role in the determination of water column stability. We consider that a major component of the turbidity is related to biological processes which are not explicitly represented in our model. Suspended material is input from the inflows and is removed by vertical settling and by outflow. For the period of our study ice cover was rarely observed in Lake Tegel we nonetheless allow for it to form as described by Patterson and Hamblin (1988).

Rogers et al. (1995) found that in a small shallow lake agreement between modelled lake temperatures and observations was improved in the wintertime by taking into account the flux of heat between the lake and the bottom sediments. In this study heat flux is modelled similarly except that the sediment temperature which is assumed in both studies to be the

annually averaged temperature is allowed to vary with depth. The heat flux q_{sed} at a layer j is calculated:

$$q_{sed}^{j} = K_{sed}\left[\frac{T_{year}^{j} - T_{water}^{j}}{Z_{sed}}\right]$$

where K_{sed} represents the thermal conductivity of the sediment , T_{year}^{j} is the average annual lake temperature for layer j, T_{water}^{j} is the temperature of the water at that layer and Z_{sed} is the thickness of the sediment layer (2 m). To demonstrate the need for taking into account interannual variability in the sediment temperatures, the average annual whole-lake temperatures are given in Table 1 for each of the studied years.

4. Description of Lake Tegel

Lake Tegel is a small lake situated in Berlin, Germany (53° 34' N, 13° 15' E). It is a vital resource for ground water replenishment and bank infiltration supplying 1/5 of Berlin's drinking water needs and plays an important role for fishing and recreation (Heinzmann and Chorus, 1994). The morphology and characteristics of the lake are given in Figure 1 and Table 2, respectively. The area and volume versus depth data required to represent lake geometry in the model were taken from Klein et al. (1993).

Lake Tegel is chiefly supplied by two heavily polluted tributaries, Tegeler Fliess (catchment area of 124 km^2) and the channel Nordgraben (catchment area of 27 km^2). Both tributaries drained waste water irrigation fields situated north of Berlin from the beginning of this century until 1990. Effluent from a waste water treatment plant are also discharged into the Nordgraben.

A high amount of nutrients were emitted into the lake via Tegeler Fliess and Nordgraben resulting in production of hypertrophic conditions by the end of the 1970's. Oxygen

deficiency had at times reached the lake surface which prompted action to alleviate the anoxic conditions. Fifteen aerators were installed in 1980 which supply a maximum capacity of 4.5 tonnes of oxygen per day at full operating capacity.

From 1980 until 1989, the aerators have been in continuous operation, including the winter months. Although intended as hypolimnetic aerators, their operation precluded stable thermal stratification in almost every summer (Heinzmann and Chorus, 1994). The presence of a thermocline is most favourable since it acts as a barrier to nutrient transport from the hypolimnion into the epilimnion hence minimizing the production rate of nutrient-limited phytoplankton (Chorus, pers. comm.). In 1990 and 1991, operation of the aerators was intermittent and turned on strategically during certain times of the year to avoid destabilizing the stratification. For instance, it has been suggested that aeration should not be carried out immediately after the spring ice break-up so as not to induce heating of the hypolimnetic waters as it is circulated to the surface (Ripl, 1993). This causes stratification to occur earlier in the year and increases the stability of the stratification during the summer months. Operating the aerators intermittently also reduces their operating costs substantially.

In order to supplement the restoration of Lake Tegel by aerators, construction began of a phosphate elimination facility (PEF) at the mouths of the Tegeler Fliess and Nordgraben which went into operation in 1985. Water is diverted from the inflowing tributaries into the PEF where the phosphates are removed from the water before they are discharged into the lake. Restoration of the lake would be accelerated if the phosphorus was prevented from redissolving from the sediments into the water column. Operation of the aerators was continued in order to prevent the redox-potential at the sediment-water interface from declining to critical values and thus keeping the phosphate immobilized in the sediments. To prevent the highly nutrient loaded Havel river water from ever entering the lake the discharge from the PEF is regulated to insure an average flow of 3 m^3/s through the lake. During dry periods when the water supply from the Tegeler Fliess and Nordgraben are low, Havel water is piped into the PEF undergoing the phosphate removal process. The pipe system also operates in the reverse direction to divert surplus water from the inflows to the

Havel during periods of flooding.

Since the operation of the phosphate elimination facility in 1985, Lake Tegel has undergone an increase in the concentration of salts. The average salt concentration in 1985 was 475 mg/l and peaked to 625 mg/l in 1987. Aluminum and iron salts are used to precipitate the phosphates out of the inflows before they are discharged into the lake. Ripl (1993) has calculated that approximately 50% of this denser inflowing water will be inserted into the hypolimnion. This inflow insertion is accounted for in the model.

Although acting mainly as an outflow, the Havel river also contributes to the inflow of Lake Tegel (Ripl, 1992). The Havel river is warmer and has a lower salt concentration (average 400 mg/l) than the epilimnion water of the lake. Hence, it is less dense than the lake causing river water to flow over the main body of the lake. This condition has become more pronounced since the increase in the lake salt concentration due to the operation of the PEF and has been accounted for in the model.

5. Description of Aerators

The aerators are of the Limnox hypolimnetic type (Senator für Bau- und Wohnungswesen des Landes Berlin, 1982) which supply air to the hypolimnion and are designed so that the thermal stratification of the lake is not upset. Other aerators are designed for the very purpose of destratifying the lake, such as the bubbler type (Klapper, 1991), but destratification is unfavourable for Lake Tegel as it would transport nutrient rich hypolimnetic water into the epilimnion. The 15 aerators are all located in the 12 - 16 meter depth regions of the lake as shown in Figure 1. A schematic of an aerator is depicted in Figure 2. Two air-cooled, oil-free compressors situated on the shore of the lake can supply up to a maximum of 91,000 m^3 of compressed air to the aerators per day which constitutes an enrichment of 4.5 tonnes of oxygen to the hypolimnion.

High pressure air is emitted into the water as tiny air bubbles by an air diffuser located half a

meter above the lake bottom. This produces an air-water mixture which, due to its higher density than the surrounding water, rises and sucks the low oxygen saturated water into the chamber. In the chamber, the oxygen in the air is allowed to diffuse into the water which is then ejected back into the hypolimnion through 6 PVC tubes. The remaining air bubbles are caught in the upper part of the chamber where they are allowed to escape to the epilimnion through a air-bleeder tube. To avoid hinderance of boating activities, the end of the air-bleeder tube is located 2.5 meters below the water surface. This air emission produces some additional currents in the epilimnion but are very minute in comparison to the currents produced by the aerators in the hypolimnion (Ripl, 1993).

6. Aerator Physics

Water is lifted a height of 2 meters from a depth of 0.5 meters above the bottom of the lake . From data published on the relation between the air flow and the discharge in the distribution tubes we represent the action of the aerators as an outflow from the bottom layers into the aerator and a subsurface inflow to the lake from the upper level. The same physical considerations for the aerator inflow and outflow apply as for the lake inflow and outflow except that for the outflow at the upper level which was handled by the inflow subroutine no initial dilution of the outflow by the surrounding lake water was allowed for (as would be the case for an underflowing river). The heat added by the compressors was calculated and found to increase the outflowing temperatures by up to 0.1°C depending on the power consumption of the particular operating levels. The density of the water drawn into the aerator had a density less than the density at the intake level on account of entrainment of less dense layers from above. When the compressor heat was added it was evident from numerical experiments that the density of the outflowing water was very close to the background density at the outflow level and was consequently inserted at this level. The insertion thickness is governed by buoyancy and inertia forces and by turbulent mixing according to an inflow Grashof and a Froude number criterion (Fischer et al., 1979). A cosine velocity distribution applies across the insertion layer thickness. The application of the two dimensional theory in the inflow and outflow routines is based on the assumption that the inflows and outflows coalesce over the

network of aerators.

Maximum aerator operation results in a water circulation of 3.5 m^3/s in the hypolimnion which corresponds to an air discharge of approximately 0.35 m^3/s (Ripl, 1993). Ripl (1993) states that the currents are evenly distributed throughout the lake hypolimnion and induce shear forces on the metalimnion contributing to the overall destratification of the water column. We have included the aerators' effect on mixing in the hypolimnion by adding the power dissipated by the aerators $p*Q$ where p is the hydrostatic pressure at the outlet and Q is the air discharge, to the dissipation of the wind stirring and river inflow potential energy used in the calculation of the hypolimnetic mixing coefficient. In general, the aerator power exceeds that of the natural forcing by several orders of magnitude.

We have attempted to account for effect of aeration on mixing in the hypolimnion in two ways. First as described above, the power dissipated by the aerators $p*Q$ is added to the dissipation of wind stirring energy and magnitude. Since this mixing energy is relatively large, it suggests that a uniform or mixed layer may be formed in the hypolimnion similarly to that of Lake Erie (Ivey and Patterson, 1984). Physically, some fraction Ca of the dissipation of aerator power $p*Q$ goes to increase the potential energy of the bottom boundary layer $\Delta\rho*g*H$ where $\Delta\rho$ is the density difference between the bottom mixed layer and the layer above, g is the acceleration of gravity and H is its thickness, according to the expression, $\Delta\rho*g*H*d(A*H)/dt = Ca*p*Q$. The increment volume of fluid entrained into the mixed layer is $d(A*H)$ where A is the layer area.

In summary, we have accounted for the aerator effect by i) the lifting of a portion of a near bottom layer to a higher level and by the associated mixing effects, ii) by the additional stirring energy in the determination of the vertical diffusivity and iii) by the formation of a bottom mixed layer according to an energy conservation principle.

There is some question about the effect of bubbles that escape from the aerator and the

possible mixing that they accomplish. Therefore, we decided to implement the bubbler plume model of Patterson and Imberger (1989) as an upper bound for this type of mixing. The reader is referred to the literature for a description of the plume dynamics and entrainment/detrainment of lake water into and out of the rising plumes (Patterson and Imberger, 1989; Schladow and Fisher, 1995). The bubble plume model of Patterson and Imberger was used without any adjustment of parameters.

7. Model Calibration and Verification

All field data used in this study were taken at the deepest point (Figure 1) which is considered to be representative of the whole lake. Unfortunately, the three other stations were not located in the main body of the lake so were not included in the field observations.

The model base case (no aeration) was calibrated with field and meteorological data from 1992, a year when the aerators were not in operation. Calibration was achieved by adjusting three free parameters, i) wind sheltering coefficient, ii) bottom sediment conductivity, and iii) extinction coefficient, to obtain the best agreement between model calculations and field temperature profiles.

First, all wind velocities were adjusted from the measurement height of 30 m to an over-lake height of 6 m by multiplying them by the empirical correction factor $[adjusted\ height\ /\ measured\ height]^{1/7}$ (National Research Council of Canada, 1985) equalling $[6\ m\ /\ 30\ m]^{1/7}$. Next, sensitivity tests were performed for various wind sheltering coefficients. In the calibration it was found that best agreement between modeled and field data was obtained for a sheltering coefficient of unity. This wind sheltering coefficient is consistent with the empirical relation of $1\text{-}8\ h/l$ (USACE, 1986) where h is the height of sheltering obstacles on the shoreline, estimated to be 25 m, and l is the effective fetch length along the major lake axis of 2.5 km.

As discussed previously it was necessary to introduce a lake bottom heat flux. This is

particularly important in the summer months since a heat loss will be induced by bank infiltration. By sensitivity tests a sediment conductivity equal to that of water (0.6 W/m/°C) gave the best fit. This may indicate that the bottom is composed of unsolidated gelatinous ooze (Likens and Johnson, 1969) which is not unreasonable for an eutrophic lake. An example of the sensitivity of the bottom heat flux can be seen in Figure 3 where temperature profiles of the model predictions are compared with field data. In the summer the model overestimates the temperatures in the water column when the sediment heat flux is not incorporated in the simulation. The sediment heat flux tends to cool the water column in the summer and warm it in the winter.

A sensitive parameter in the model is the extinction coefficient. This parameter controls the depth over which solar radiation penetrates the water column. The greater the extinction coefficient is, the shallower the depth of penetration of solar radiation. The extinction coefficients were calculated from the Secchi depth measurements using the empirical relationship:

$$\textit{Extinction Coefficient}\left(\frac{1}{m}\right) = \frac{\textit{Constant}}{\textit{Secchi Depth (m)}}$$

where *Constant = 1.3* gave the closest fit of model predictions to the field data. We assumed this constant to apply for all other years. The relatively high and fluctuating extinction coefficients shown in Figure 4 are due to the varying production rates of phytoplankton biomass during the year. Since the production of biomass is not accounted for in the model for the other years, as well, we have taken the calculated extinction coefficients based on the Secchi depth observations. Annual averages of the extinction coefficients used are given in Table 1.

Meteorological data that served as forcing functions for the model are shown in Figure 5. The location of the meteorological station (see Figure 1) is approximately 14 km from Lake

Tegel. It is assumed that this extrapolation to the conditions over the lake will not result in a serious bias.

Contour plots of the simulation and the field temperatures with respect to depth are presented in Figure 6 for the calibration year 1992. It is evident that the annual thermal regime is closely simulated. The magnitude of the differences between modelled and observed temperatures is consistent with other applications of the model DYRESM to lakes (Boyce et al., 1992) and Hollan et al., 1990) despite the fact that the field data were taken at only one observational point and meteorological data were extrapolated. The other studies were based on lake-wide averages of many profiles and overlake meteorological data.

8. Bubbler and Stirrer Modules

The bubbler and stirrer routines were incorporated into the calibrated model and tested for the years 1987, 1988, 1990, and 1991 when the aerators were in use. For each of these years, the model was run as a i) base case (no aeration), ii) stirrer and iii) bubbler and the temperature profiles were compared of each of the cases. The base case was included in order to highlight the thermal response of aeration. A summary of the aerator operation is given in Figure 7. Full operation of the system refers to all 15 aerators and both compressors in operation. Only for 1991 and 1992 were such data available. For the other years estimates were made based on the reports of Ripl (1992) (1993).

9. Thermal Response to Aeration

(a) Continuous Operation

For the years 1980 until 1989 during which the aerators were operated continuously we selected the year 1988 to illustrate the thermal response of continuous aeration. A series of temperature and temperature difference contour plots are given in Figures 8, 9 and 10 for the base case, bubbler module and stirrer module, respectively. The field data has been

reproduced from the graphs of Ripl (1993) in order to make comparison with model results easier. Field sampling dates were unavailable. As might be expected in the unaerated case, the model indicates a higher rate of summer stratification and for a longer period compared to the field data. This is readily evidenced by the 15°C contour line in the model temperature predictions from May until September. When the bubbler routine is activated the temperature gradient is less steep in the model which matches the field data more closely than in the unaerated case. This is seen in the corresponding temperature difference contour plots. In the base case (unaerated), the model greatly underestimated the temperature in the hypolimnion during the summer months (hence large negative values). These differences are significantly reduced when the bubbler is activated. The temperature differences in the epilimnion do not change considerably indicating that the principal effect of the bubblers is to mix and entrain the hypolimnion. The aerators are continuously in operation during this year but not at full capacity (see Figure 7) allowing for the hypolimnion to be supplied with air but preventing complete destratification to occur.

Figure 10 shows the impact of the stirrer module on the heat budget of the lake. For the summer months the model greatly underestimates (negative values) the temperature predictions for both the hypolimnion and the epilimnion with individual volume-weighted errors as large as 6°C. Sensitivity tests indicate that the implementation of a benthic mixed layer due to aeration did not improve the agreement between observations and stirrer module simulations, no matter what values of the parameter *Ca* were assumed. Because the bottom layer is cooled by the heat flux from the sediments, the stirring action simply transports and distributes this colder water from the bottom layers throughout the hypolimnion. This reduces the temperature of the hypolimnetic waters considerably. The opposite effect occurs in the winter months when the bottom sediments have a higher temperature than the water column. Hence the temperature difference contour plot shows an overestimation of the model temperature calculations (positive values) in the winter. The drawing of warmer water from the lake bottom essentially warms the lake.

This pattern of results is typical for all the aeration years as may be seen in the tabulation of

errors in Table 3. For the purpose of comparison with other years an overall rms error was computed based on volume-weighting the squares of the temperature differences.

(b) Intermittent Operation

In 1990 and 1991 improvements in water quality permitted the occasional use of the aerators. To illustrate the behaviour of the model for a year when the aerators are run intermittently contour plots of the temperature differences for the base case, bubbler and stirrer are given in Figure 11 for 1990. Comparison of the plots reveals a marked improvement of the simulated results when the bubbler routine is incorporated into the model and underscores the module's applicability for the development of various operational strategies. For the stirring routine, however, the temperatures are, again, greatly underestimated in the summer and overestimated in the winter throughout the entire water column.

10. Discussion and Conclusions

A mathematically based water quality model has been shown capable of modelling the thermal structure and to a lesser extent the total dissolved and suspended solids distributions of a small urban lake on an annual basis. Due to the shallowness of the lake, simulations were found to be sensitive to the flux of heat from the sediments. During periods of full aeration, the aerator power exceeded, in general, that of natural wind and river inflow forcing by several orders of magnitude.

Via numerical experimentation the behaviour of two approaches to artificial stirring representing two extremes, strictly hypolimnetic mixing and, alternately, bubbler plume destratification has been examined. Surprisingly, it has been found that for aerator design in Lake Tegel its mixing may be well represented as a conventional bubble plume and not as a hypolimnetic aerator. This major conclusion is partially supported by Heinzmann and Chorus (1994) who observe destratification of the lake during periods of aerator operation. The finding that model errors were not reduced by treating the effect of aeration as a hypolimnetic

mixed layer implies that the aerators do not mix the hypolimnion as expected but rather transport hypolimnetic water upwards to the thermocline.

The action of the aerators interacts with natural mixing processes. The buoyant plumes lift more dense water into the metalimnion thereby thinning the epilimnion. A thinner epilimnion enhances the vertical shear across the thermocline resulting in a higher rate of entrainment of hypolimnetic water into the epilimnion thereby reducing the strength and duration of the stratified periods.

Further research is still required in extending the model to treat other water quality constituents such as dissolved oxygen, biomass and nutrients. On account of its extensive data sets, particularly in time, Lake Tegel would be an excellent natural laboratory for research on simulation of lake and reservoir water quality with and without lake aeration.

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List of Table Captions

Table 1: Average annual whole-lake temperatures and extinction coefficients.

Table 2: Morphological and hydrological data of Lake Tegel.

Table 3: Average annual whole-lake temperature rms errors between simulations (base case bubbler and stirrer) and field data. Errors are volume-weighted.

List of Figure Captions

Figure 1: Location of study area, observational points, aerator network, major inflows and outflows and simplified lake bathymetry. Temperature profiles were taken at x,the deepest point.

Figure 2: Schematic of the hypolimnetic aerator. Modified from Senator für Bau- und Wohnungswesen (1981).

Figure 3: The effect of the sediment heat flux on temperature profiles (August 3, 1992).

Figure 4: Extinction coefficients (1992).

Figure 5: Meteorological data used for forcing functions in the 1992 model simulation: a) short wave radiation, b) incoming long-wave radiation, c) unadjusted wind speed, d) air temperature and e) relative humidity. Data kindly provided by the Meteorological Institute of the Free University of Berlin.

Figure 6: Contour plots of the temperature differences (a) between the model results (b) and field data (c) for the model calibration year 1992. The temperature difference is defined as the modelled temperature minus the observed temperature. Hence, positive and negative

values correspond to model over- and underestimations, respectively. Tics on (c) indicate days of measurement.

Figure 7: Aerator operational curves (Ripl, 1993).

Figure 8: Same as Figure 6 but for the 1988 base case.

Figure 9: Same as Figure 6 but for the 1988 bubbler module.

Figure 10: Same as Figure 6 but for the 1988 stirrer module.

Figure 11: Contour plots of the temperature differences (see Figure 6) between the model results and the field data for the a) base case, b) bubbler module and c) stirrer module for 1990.

Table 1:

	1987	1988	1990	1991	1992
Whole-lake Temperature (°C)	10.5	11.0	10.6	13.9	13.0
Extinction Coefficient (1/m)	0.72	0.72	0.63	0.73	0.79

Table 2:

Surface Area	400 ha
Volume	24.6 million m^3
Maximum Depth	16 m
Mean Depth	6 m
PEF Inflow	$\approx$ 3 m^3/s
Havel Inflow	$\approx$1.8 m^3/s
Residence Time	$\approx$ 60 days

Table 3:

	1987	1988	1990	1991	1992
Base Case	1.45	1.41	1.23	1.82	0.94
Bubbler	1.34	1.41	1.15	1.58	---
Stirrer	2.92	2.46	1.68	2.29	---

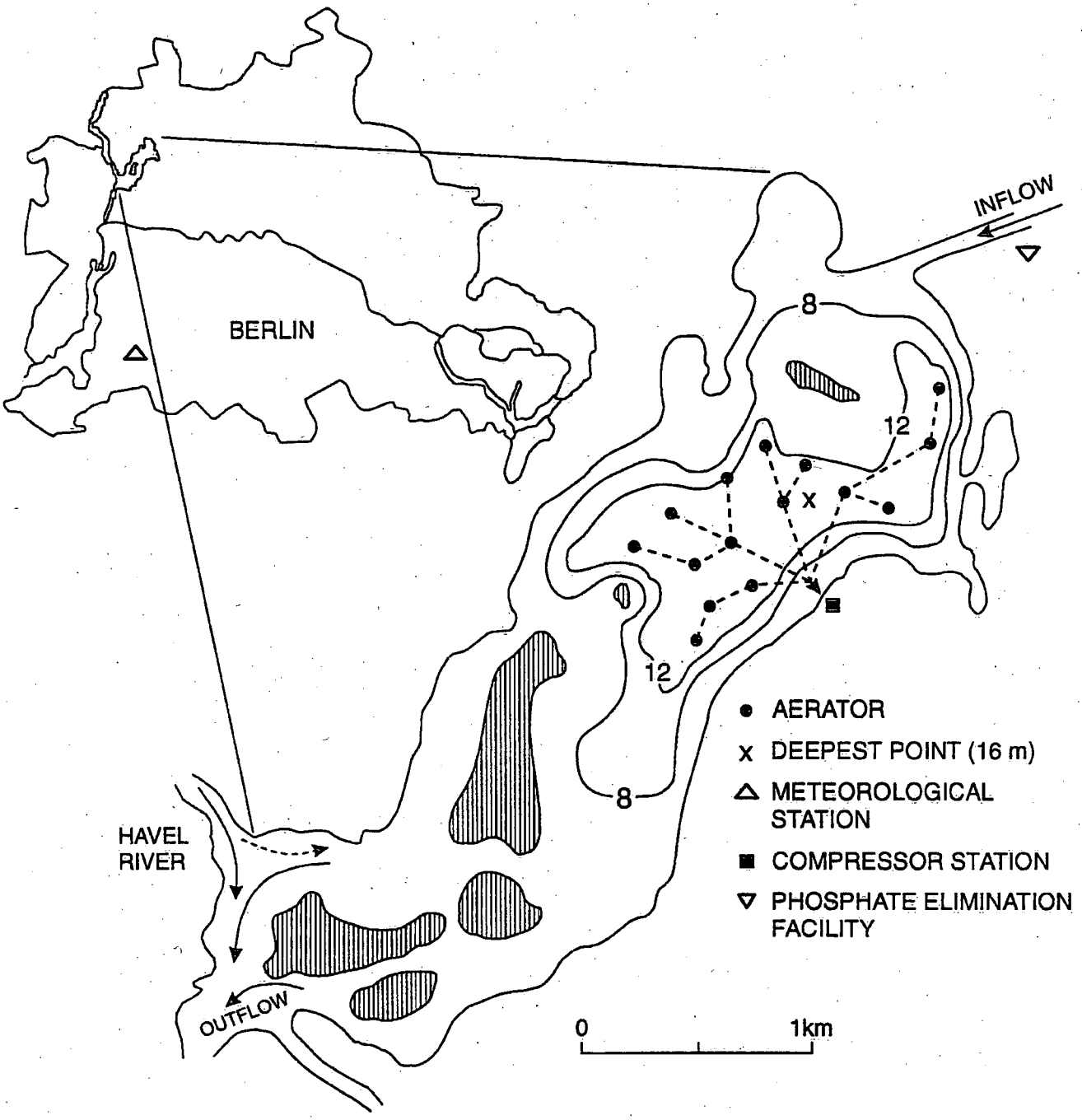
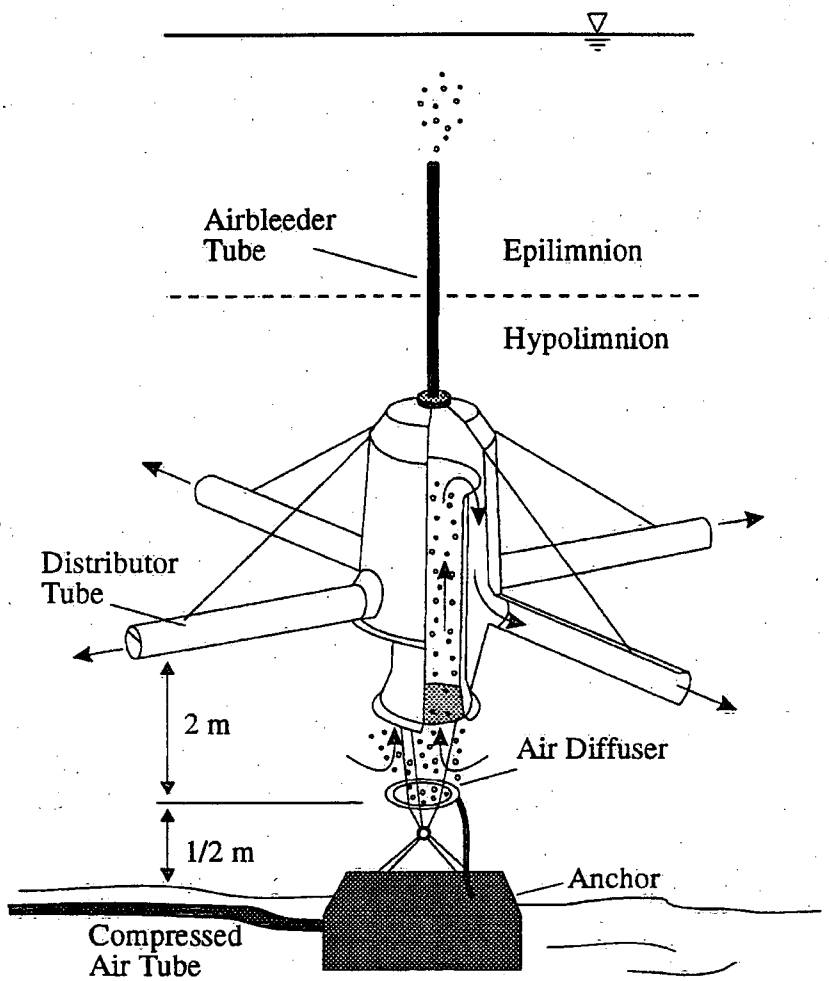
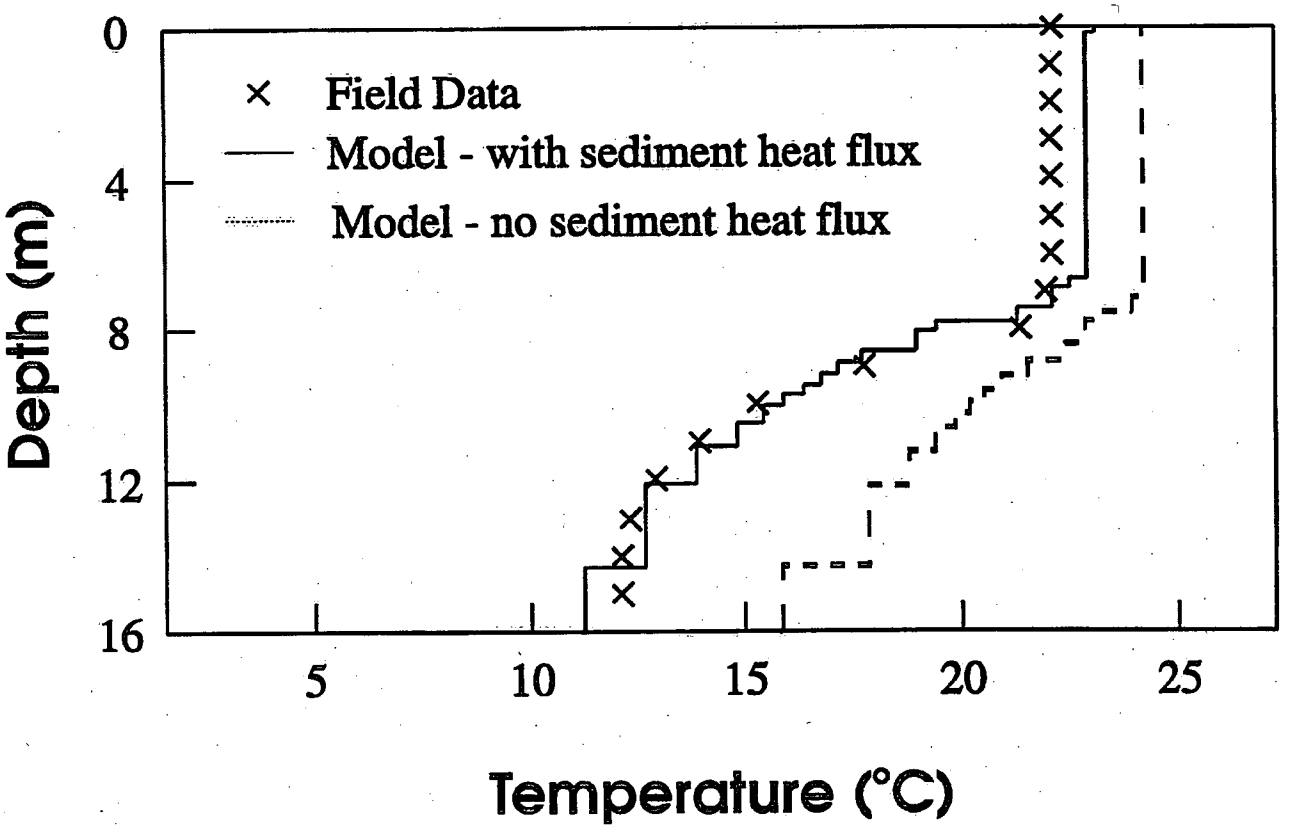
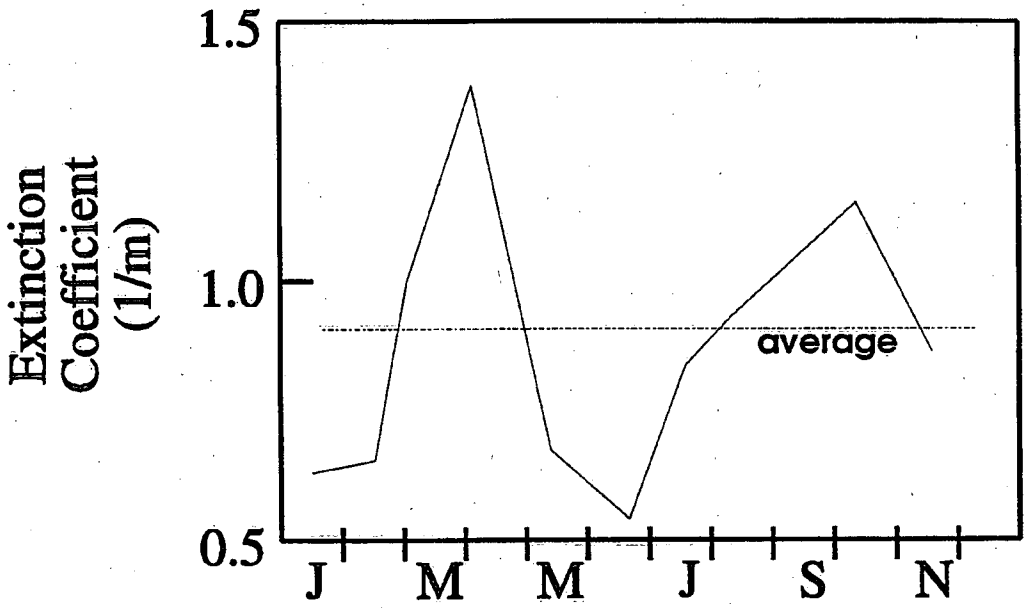
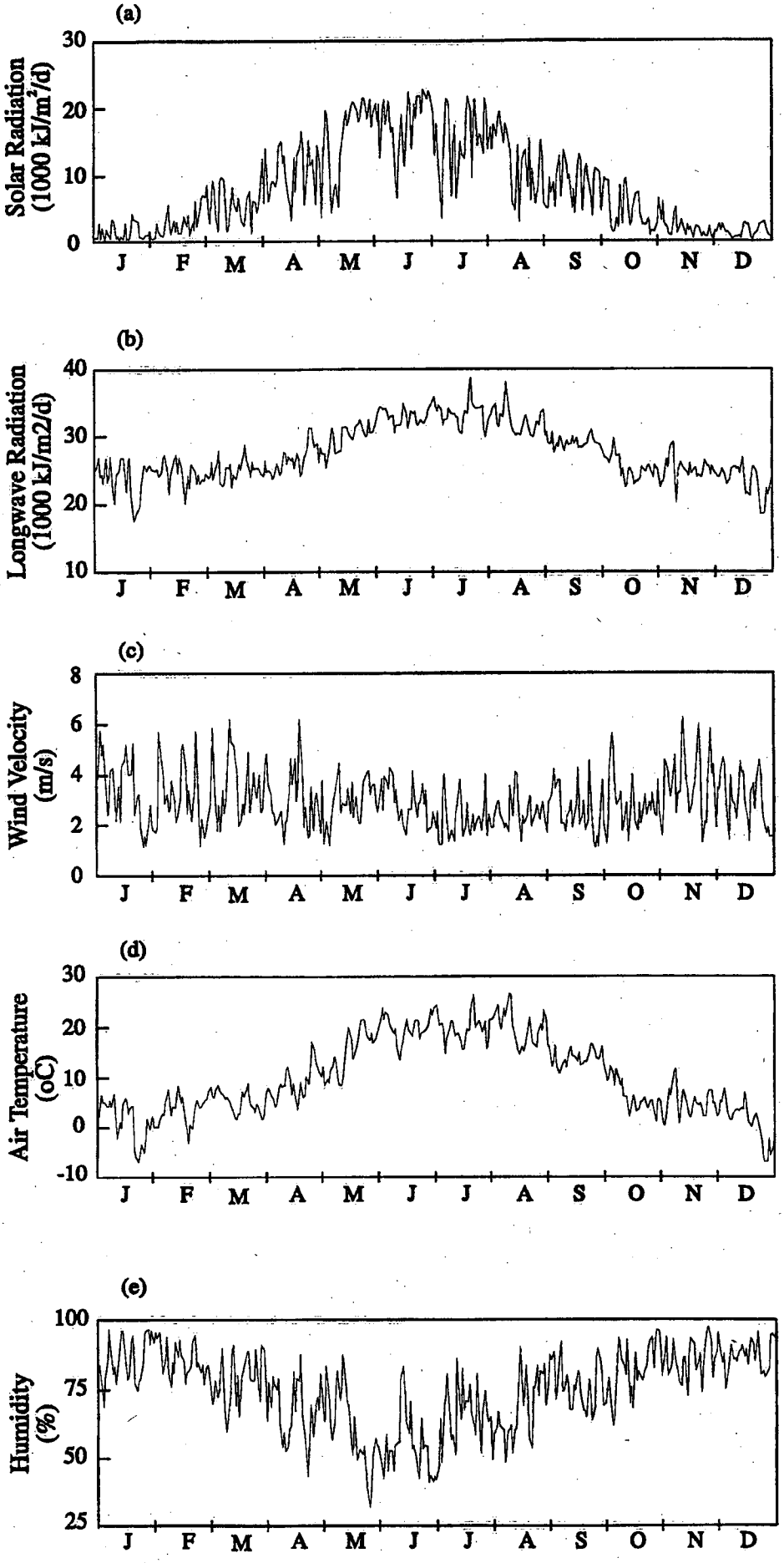

INFLOW
BERLIN
8
12
X
12
8
HAVEL
RIVER
OUTFLOW
AERATOR
X DEEPEST POINT (16 m)
METEOROLOGICAL STATION
COMPRESSOR STATION
PHOSPHATE ELIMINATION FACILITY
0
1km

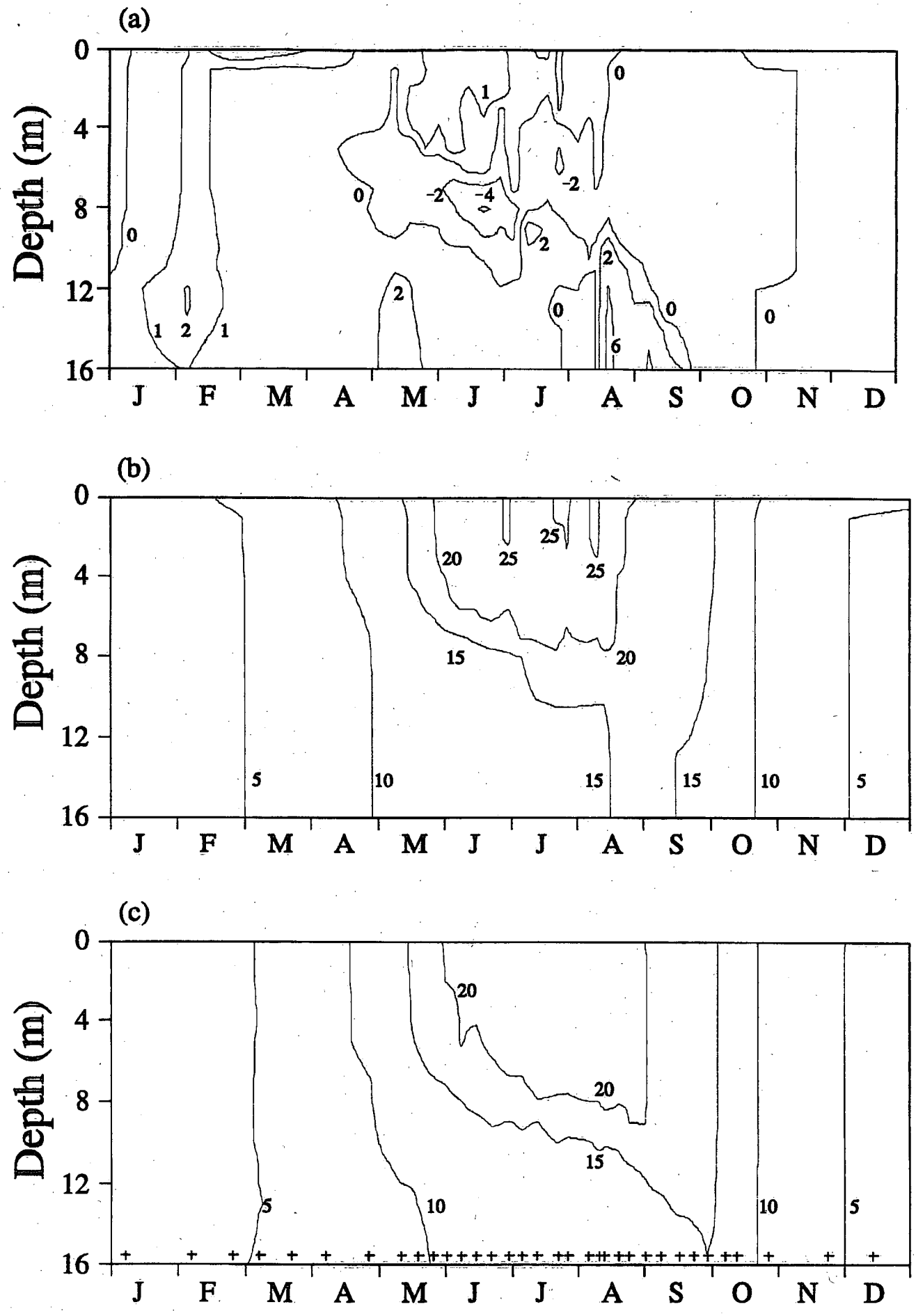
Fig 1.


Airbleeder
Tube
Epilimnion
Hypolimnion
Distributor
Tube
2 m
Air Diffuser
1/2 m
Anchor
Compressed
Air Tube


Field Data
Model - with sediment heat flux
Model - no sediment heat flux
Depth (m)
0
4
8
12
16
5
10
15
20
25
Temperature (°C)


Extinction Coefficient (1/m)
1.5
1.0
0.5
average
J
M
M
J
S
N


(a)
Solar Radiation (1000 kJ/m²/d)
30
20
10
0
J F M A M J J A S O N D
(b)
Longwave Radiation (1000 kJ/m2/d)
40
30
20
10
J F M A M J J A S O N D
(c)
Wind Velocity (m/s)
8
6
4
2
0
J F M A M J J A S O N D
(d)
Air Temperature (oC)
30
20
10
0
-10
J F M A M J J A S O N D
(e)
Humidity (%)
100
75
50
25
J F M A M J J A S O N D



92 calibration

Fig 6.

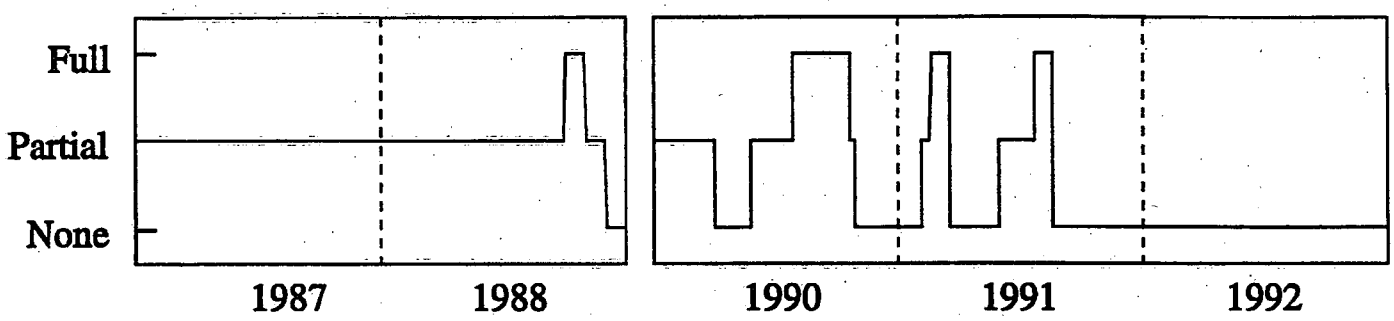
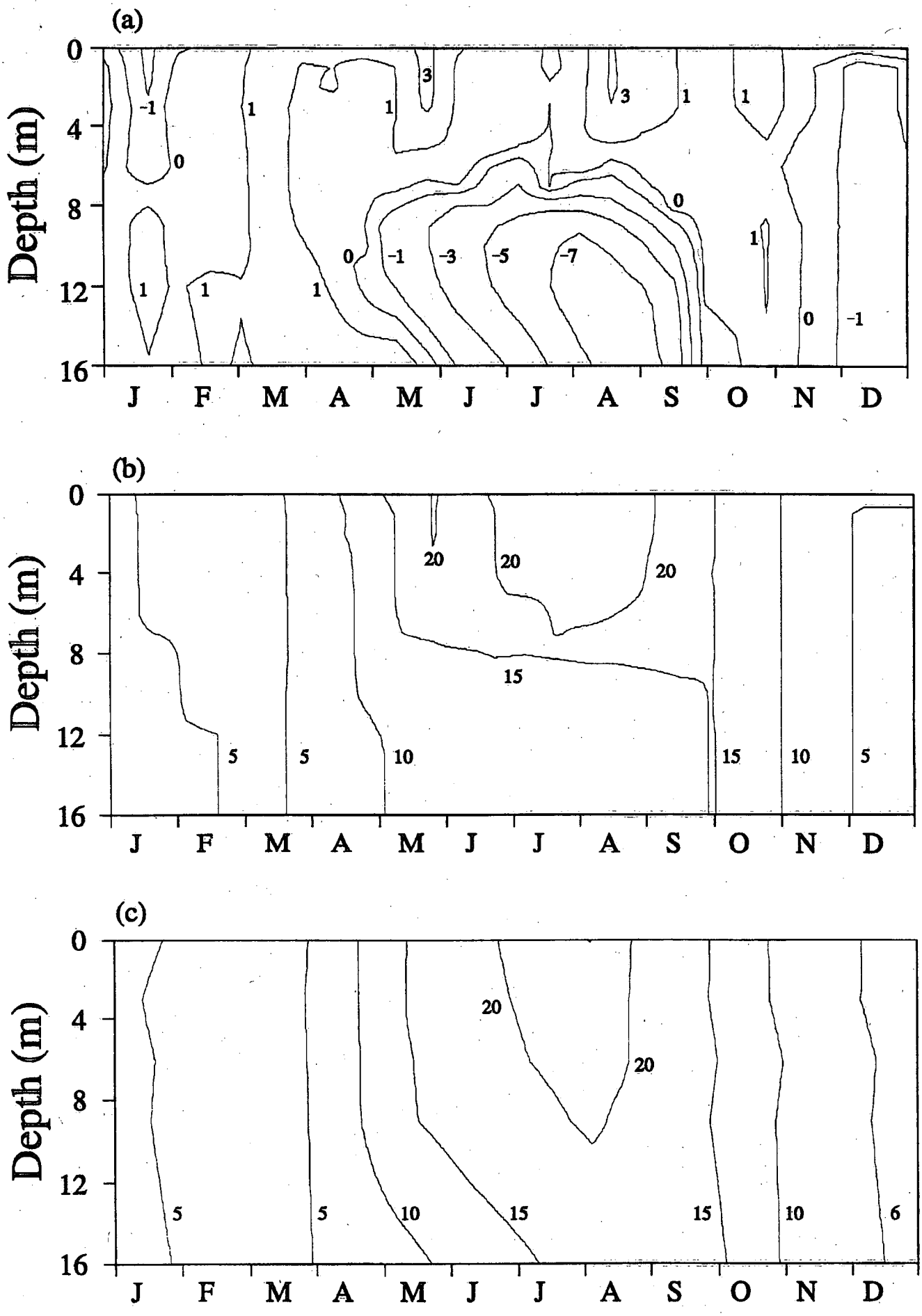
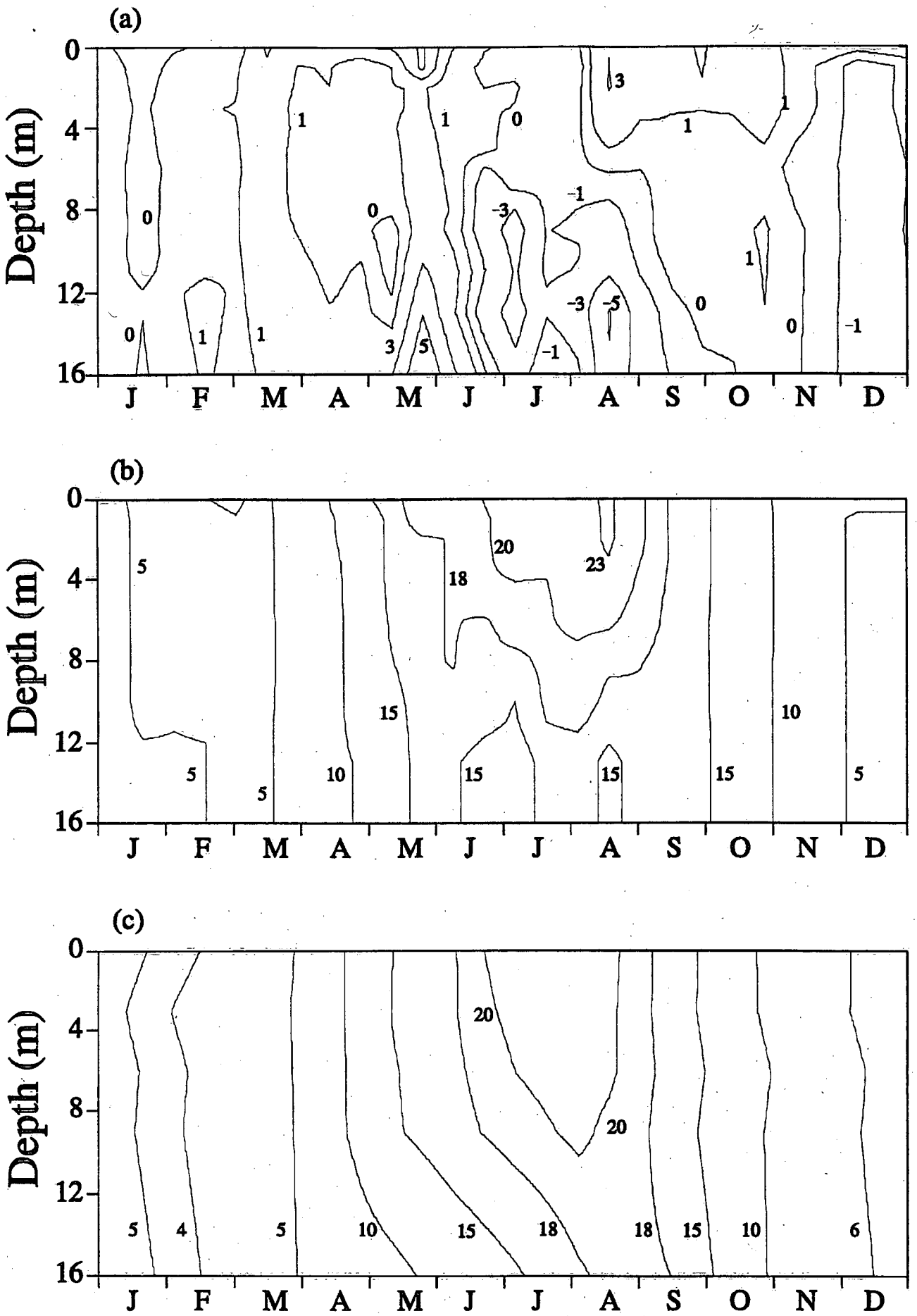
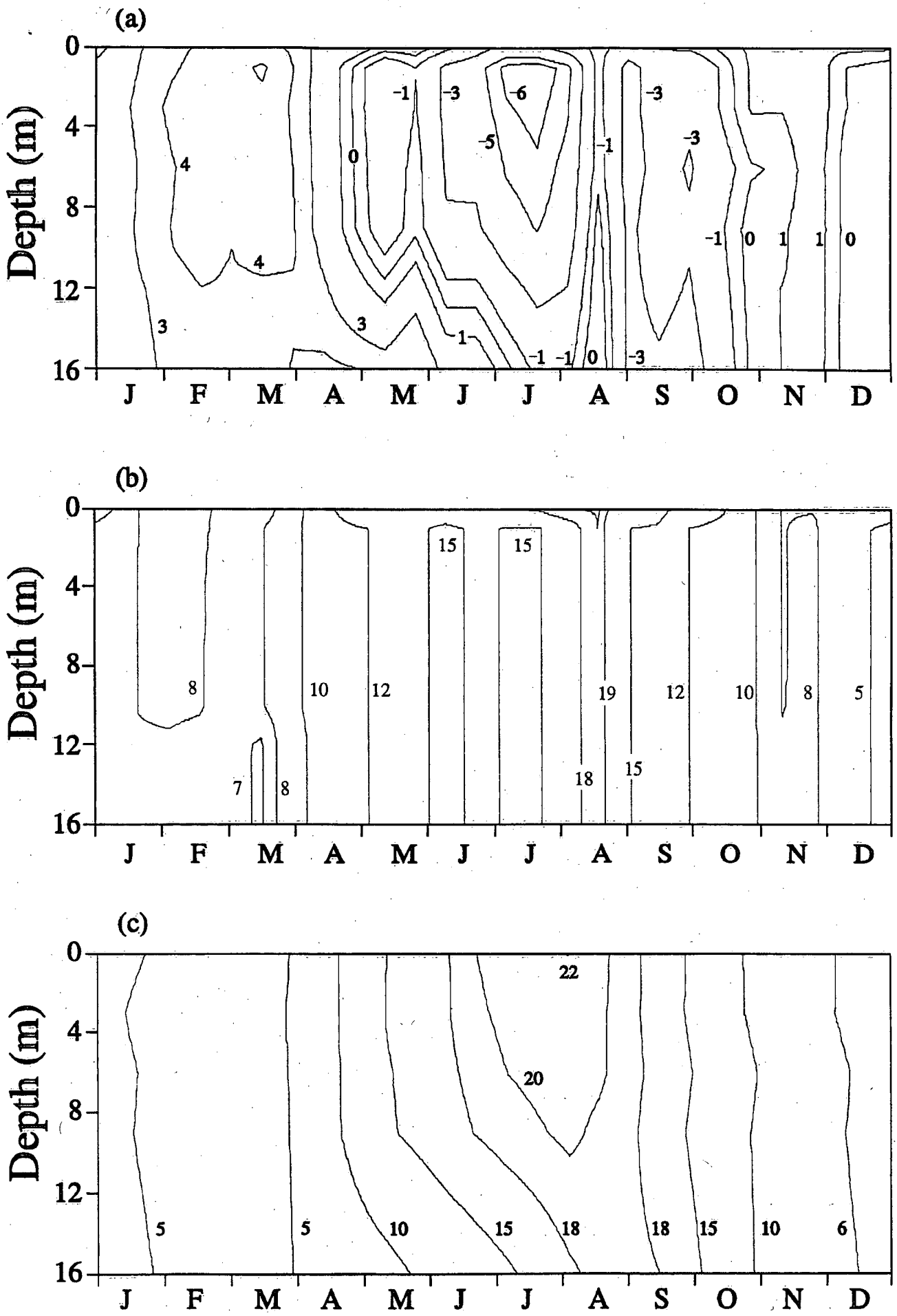
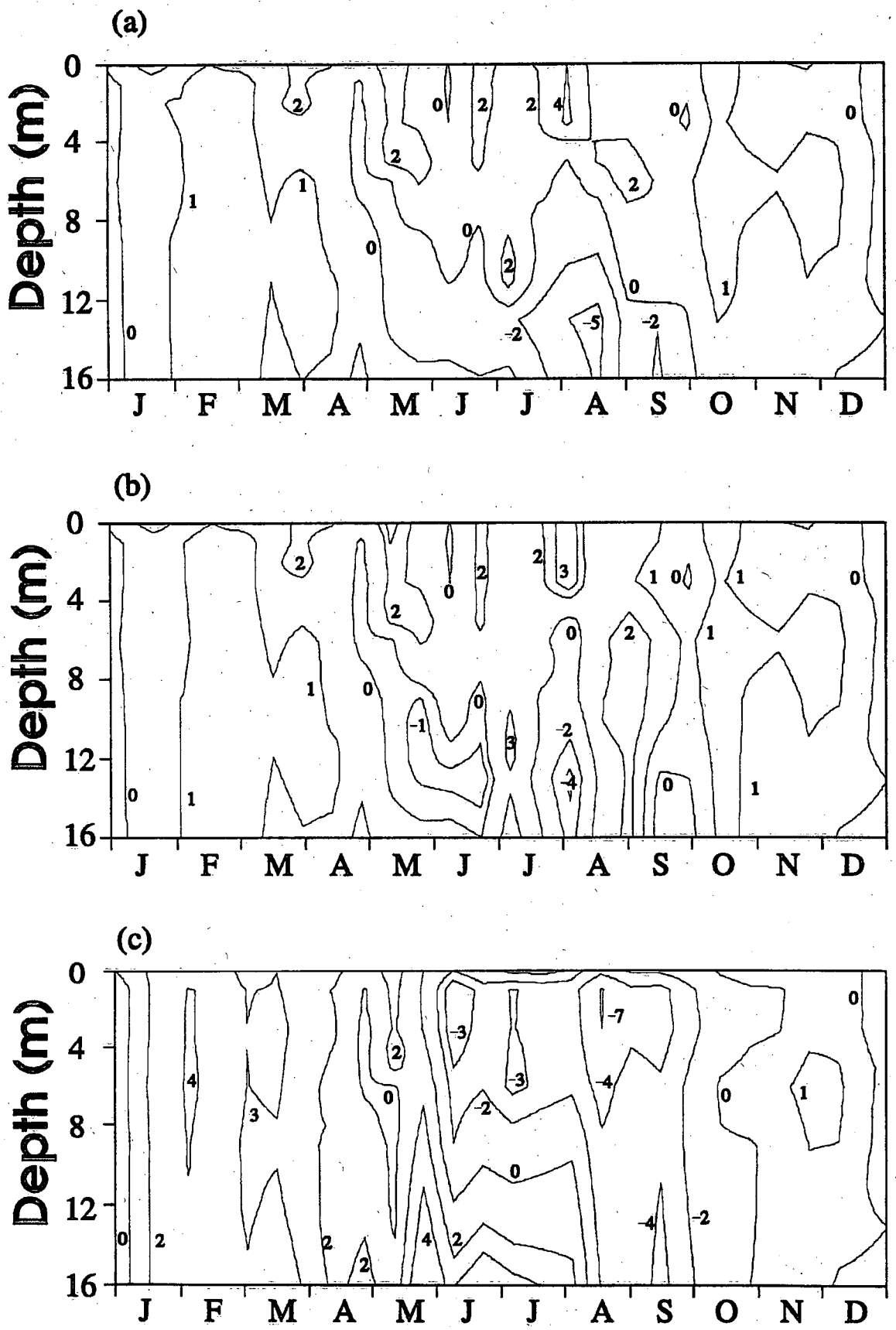


Fig 7.


(a)
Depth (m)
0
4
8
12
16
J F M A M J J A S O N D
-1
0
1
1
1
1
3
1
3
1
1
0
1
0 -1 -3 -5 -7
1
1
0
-1
(b)
Depth (m)
0
4
8
12
16
J F M A M J J A S O N D
20
20
20
15
5
5
10
15
10
5
(c)
Depth (m)
0
4
8
12
16
J F M A M J J A S O N D
20
20
5
5
10
15
15
10
6


(a)
Depth (m)
0
4
8
12
16
J F M A M J J A S O N D
(b)
Depth (m)
0
4
8
12
16
J F M A M J J A S O N D
(c)
Depth (m)
0
4
8
12
16
J F M A M J J A S O N D


(a)
Depth (m)
0
4
8
12
16
J F M A M J J A S O N D
4
4
3
-1
-3
-6
-5
0
3
1
-1
-1
0
-3
-1
-3
-3
-1
0
1
1
0
(b)
Depth (m)
0
4
8
12
16
J F M A M J J A S O N D
8
7
8
10
12
15
15
18
19
15
12
10
8
5
(c)
Depth (m)
0
4
8
12
16
J F M A M J J A S O N D
5
5
10
15
18
22
20
18
15
10
6


(a)
Depth (m)
0
4
8
12
16
J F M A M J J A S O N D
(b)
Depth (m)
0
4
8
12
16
J F M A M J J A S O N D
(c)
Depth (m)
0
4
8
12
16
J F M A M J J A S O N D

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